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Modeling Geologic Storage of Carbon Dioxide: Comparison of Non-hysteretic and Hysteretic Characteristic Curves

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TOUGH2 has been used extensively in the past few years to model geologic storage of CO_2 in brine-saturated formations. At depths commonly considered for CO_2 storage (>800 m), CO_2 primarily exists as a gas-like supercritical phase, which is the non-wetting phase, while some CO_2 dissolves in the brine, which is the wetting phase. The simplest way to model the interaction between the two phases is to use non-hysteretic characteristic curves. That is, the capillary pressure and relative permeabilities depend only on the local saturation at the current time. A more sophisticated approach is a hysteretic formulation, in which capillary pressure and relative permeabilities depend not only on the current value of the local saturation, but on the history of the local saturation and the process that is occurring: drainage (replacement of wetting phase with non-wetting phase) or wetting (replacement of non-wetting phase with wetting phase). The use of hysteretic characteristic curves is not so critical for the simulation of CO_2 injection periods when the plume is continuously growing, because all locations follow the primary drainage branch of the capillary pressure curve, and this branch can be replicated using a non-hysteretic formulation. However, for post-injection periods, when the CO_2 plume moves upward and updip due to buoyancy forces, different locations experience drainage and wetting at different times, necessitating the use of a hysteretic formulation. A key difference between the drainage and wetting processes is the value of residual gas saturation, which is generally considered to be near zero for drainage but may be quite large for wetting, enabling a significant portion of the CO_2 plume to become trapped as it migrates.

TOUGH2 has had the capability to use hysteretic characteristic curves for many years. Hysteretic capillary pressure functions were introduced in the late 1980's and hysteretic relative permeability functions were added about ten years later. However, the hysteretic version of TOUGH2 was not numerically efficient enough to be used for 2D or 3D CO_2 sequestration problems. One crucial modification that we made is to ensure that capillary pressure and relative permeability functions are continuous and differentiable within and beyond the turning-point saturations that nominally limit their domain. This is required because actual saturations may fall outside of this domain due to dissolution of CO_2 or numerical effects. Additionally, an option has been added to delay curve switching to the end of each time step. This has the effect of making the fully implicit time-stepping normally employed by TOUGH2 partially explicit. With these modifications, hysteretic simulations are computationally competitive with non-hysteretic simulations.

Three idealized problems related to CO_2 sequestration are simulated using both hysteretic and non-hysteretic formulation for characteristic curves. The first problem considers leakage of CO_2 from the storage formation to the ground surface, the second examines the role of heterogeneity within the storage formation, and the third treats migration through a steeply-dipping, very high-permeability sand where field observations are available to validate numerical results.